

TITLE

FLUOROUS TAGGING COMPOUNDS AND METHODS OF USE THEREOF

Governmental Interests

5 This invention was made with government support under grant CA 78039 awarded by the National Institutes of Health. The government has certain rights in this invention.

Field of the Invention

10 The present invention relates to fluororous tagging or protecting compounds and to methods of use thereof, and especially, to fluororous tagging compounds suitable for use with hydroxy- and amine-bearing organic compounds.

Background of the Invention

15 In traditional organic chemistry, compounds are synthesized as pure substances through well-planned reactions and careful separation. However, in a number of fields, including drug discovery, catalyst design and new material development, tens of thousands of organic compounds must be synthesized and tested to discover a few
20 active ones. In the pharmaceutical industry, for example, synthesizing such a large number of compounds in the traditional way is too slow compared to the rapid emergence

of new biological targets. The productivity of orthodox solution (liquid) phase organic synthesis is severely limited by tedious separation processes for the purification of products. Techniques integrating organic reactions with rapid purification/separation procedures are thus highly desirable.

Recently, fluorous synthetic and separation techniques have attracted the interest of organic chemists. In fluorous synthetic techniques, reaction components are typically attached to fluorous groups or tags such as perfluoroalkyl groups to facilitate the separation of products. Organic compounds are readily rendered fluorous by attachment of an appropriately fluorinated phase label or tag. In general, fluorous-tagged molecules partition preferentially into a fluorous phase while non-tagged ones partition into an organic phase.

The fluorous tag preferably fulfills a double role as protective group and phase tag and is removed in the final step(s) of the synthesis. The viability of a fluorous synthesis plan depends greatly on the availability of suitable fluorous protecting groups, but only a few fluorous tags are currently available.

In that regard, the fluorous phase label or tag most often used in fluorous synthesis has been the silane $(\text{C}_{10}\text{F}_{21}\text{CH}_2\text{CH}_2)_3\text{SiBr}$ **1**. In general, the silane is attached to alcohol-bearing substrates using standard conditions to result in a silyl ether, and can be cleaved with fluoride. The silane, however, cannot be recycled. In addition, the

powerful electron withdrawing effect of three fluororous chains makes the silyl ether rather labile towards nucleophiles and other polar reactions. Thus, although fluororous synthetic and/or separation techniques are promising, such techniques are currently limited by a lack of availability of suitably versatile fluororous tags.

It is thus very desirable to develop improved fluororous tagging compounds.

Summary of the Invention

For the further development of fluororous phase chemistry into a practical strategy in, for example, combinatorial and parallel synthesis, a variety of fluororous phase labels must be made available. The present invention provides fluororous tags that can be prepared in large quantity, can be installed and removed from a substrate using mild reaction conditions, and can be recyclable after cleavage. In addition, the fluororous tags of the present invention are tolerant, as a group, to a wide range of reaction conditions, such that an appropriate label can be chosen which is amenable to substantially any given sequence of reactions.

The resulting fluororous "tagged" compound can be used in a wide variety of fluororous reaction and/or separation techniques. Several fluororous reaction and separation techniques are disclosed, for example, in U.S. Patent Nos. 5,859,247 and 5,777,121, the disclosures of

which are incorporated herein by reference. The tagging compounds of the present invention are particularly suitable for tagging of compounds bearing hydroxyl groups or nitrogen groups such as amine groups.

5 As used herein, the term "fluorous", when used in connection with an organic (carbon-containing) molecule, moiety or group, refers generally to an organic molecule, moiety or group having a domain or a portion thereof rich in carbon-fluorine bonds (for example, fluorocarbons or
10 perfluorocarbons, fluorohydrocarbons, fluorinated ethers, fluorinated amines and fluorinated adamantyl groups). For example, perfluorinated ether groups can have the general formula $-(\text{CF}_2)_x\text{O}(\text{CF}_2)_y\text{CF}_3$, wherein x , y and z are integers. Perfluorinated amine groups can, for example,
15 have the general formula $-(\text{CF}_2)_x(\text{NR}^a)\text{CF}_2)_y\text{CF}_3$, wherein R^a can, for example, be $(\text{CF}_2)_n\text{CF}_3$, wherein n is an integer. Fluorous ether groups and fluorous amine groups suitable for use in the present invention need not be perfluorinated, however. The term "fluorous compound,"
20 thus refers generally to a compound comprising a portion rich in carbon-fluorine bonds. As used herein, the term "perfluorocarbons" refers generally to organic compounds in which all hydrogen atoms bonded to carbon atoms have been replaced by fluorine atoms. The terms "fluorohydrocarbons"
25 and "hydrofluorocarbons" include organic compounds in which at least one hydrogen atom bonded to a carbon atom has been replaced by a fluorine atom. A few examples of suitable fluorous groups Rf for use in the present invention include, but are not limited to, $-\text{C}_4\text{F}_9$, $-\text{C}_6\text{F}_{13}$, $-\text{C}_8\text{F}_{17}$,

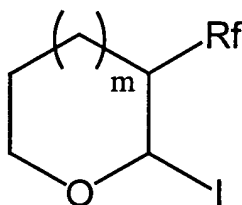
-C₁₀F₂₁, -C(CF₃)₂C₃F₇, -C₄F₈CF(CF₃)₂, -CF₂CF₂OCF₂CF₂OCF₃,
-CF₂CF₂(NCF₂CF₃)CF₂CF₂CF₃, and fluorous adamantyl groups.

As used herein, the term "tagging" refers generally to attaching a fluorous moiety or group (referred to as a "fluorous tagging moiety" or "tagging group") to a compound to create a "fluorous tagged compound". Separation of the tagged compounds of the present invention is achieved by using fluorous separation techniques that are based upon differences between/among the fluorous nature of a mixture of compounds. As used herein, the term "fluorous separation technique" refers generally to a method that is used to separate mixtures containing fluorous molecules or organic molecules bearing fluorous domains or tags from each other and/or from non-fluorous compounds based predominantly on differences in the fluorous nature of molecules (for example, size and/or structure of a fluorous molecule or domain or the absence thereof). Fluorous separation techniques include but are not limited chromatography over solid fluorous phases such as fluorocarbon bonded phases or fluorinated polymers. See, for example, Danielson, N.D. et al., "Fluoropolymers and Fluorocarbon Bonded Phases as Column Packings for Liquid Chromatography," J. Chromat., 544, 187-199 (1991). Examples of suitable fluorocarbon bonded phases include commercial Fluofix® and Fluophase™ columns available from Keystone Scientific, Inc. (Bellefonte, PA), and FluoroSep™-RP-Octyl from ES Industries (Berlin, NJ). Other fluorous separation techniques include liquid-liquid based separation methods such as liquid-liquid extraction or

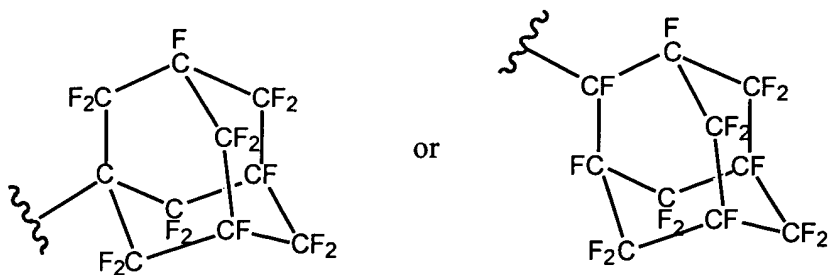
countercurrent distribution with a fluorous solvent and an organic solvent.

Preferably, the molecular weight of the fluorous tags of the present invention does not exceed about 2,500. More preferably, the molecular weight does not exceed about 1,750. Even more preferably the molecular weight does not exceed about 1200. Compounds may bear more than one fluorous tag of the present invention.

In one aspect, the present invention provides a method of increasing the fluorous nature of a compound, including the step of reacting the compound with at least one second compound having the formula:



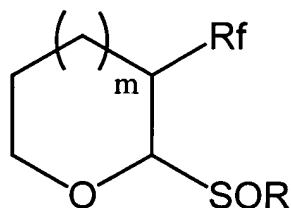
wherein Rf is a fluorous group and m is 0, 1 or 2 (that is, the ring can be a five-, six-, or seven-membered ring). The fluorous group can, for example be a fluorohydrocarbon group (for example, fluorous alkyl groups, including fluorous adamantyl groups), a perfluorocarbon group, a fluorinated ether group or a fluorinated amine group. Perfluoroadamantyl group suitable for use in the present invention can, for example, have the following formulas:



As used herein, the terms "alkyl", "aryl" and other substituent groups refer generally to both unsubstituted and substituted groups unless specified to the contrary. Unless otherwise specified, alkyl groups are hydrocarbon groups and are preferably C₁-C₁₅ (that is, having 1 to 15 carbon atoms) alkyl groups, and more preferably C₁-C₁₀ alkyl groups, and can be branched or unbranched, acyclic or cyclic. The term "aryl" refers to phenyl (Ph) or naphthyl, substituted or unsubstituted. The term "alkylene" refers to bivalent forms of alkyl.

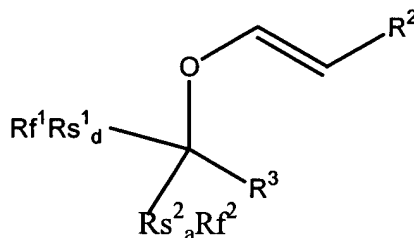
The groups set forth above, can be substituted with a wide variety of substituents. For example, alkyl groups may preferably be substituted with a group or groups including, but not limited to aryl groups. Aryl groups may preferably be substituted with a group or groups including, but not limited to, alkyl groups or other aryl groups.

In another aspect, the present invention provides a method of increasing the fluorous nature of a compound, including the step of reacting the compound with at least one second compound having the formula:



wherein Rf is a fluorous group as defined above, R¹ is a an alkyl group or an aryl group and m is 0, 1 or 2.

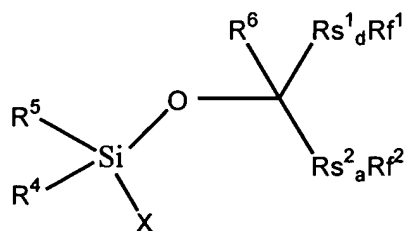
A method of increasing the fluorous nature of a
 5 compound, including the step of reacting the compound with
 at least one second compound having the formula:



wherein Rf¹ and Rf² are independently, the same or
 different, fluorous groups, Rs¹ is a spacer group, d is 1 or
 10 0 (that is, the spacer group can be present or absent), Rs²
 is a spacer group, a is 1 or 0, R² is a H, an alkyl group or
 an aryl group, R³ is H or -Rs³_eRf³, wherein, Rs³ is a spacer
 group, e is 1 or 0, and Rf³ is a fluorous group. Numerous
 types of spacer groups or linkages can be used in the
 15 present invention. Examples of spacer groups suitable for
 use herein include, but are not limited to, alkylene groups
 (preferably, C₁-C₆ alkylene groups), 1,2-, 1,3-, or
 1,4-divalent phenyl groups or alkoxy alkylene groups (for
 example, -O(CH₂)_x-). As used herein, the term "alkylene"
 20 refers generally to a bivalent form of an alkyl group (for

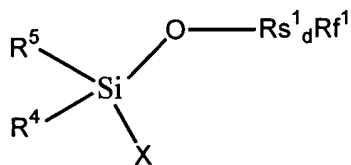
example, $-(CH_2)_m-$ Alkylene groups may be substituted or unsubstituted.

The present invention also provides a method of increasing the fluorous nature of a compound, including the step of reacting the compound with at least one second compound having the formula:



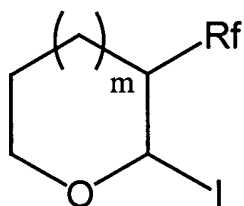
wherein Rf^1 and Rf^2 are independently, the same or different, fluorous groups, Rs^1 is a spacer group, d is 1 or 0 (that is, the spacer group can be present or absent), Rs^2 is a spacer group, a is 1 or 0,, R^4 is an alkyl group or an aryl group, R^5 is an alkyl group or an aryl group, R^6 is H, an alkyl group, or a fluorinated alkyl group, and X is Cl, Br or I.

In another aspect, the present invention provides a method of increasing the fluorous nature of a compound, including the step of reacting the compound with at least one second compound having the formula:

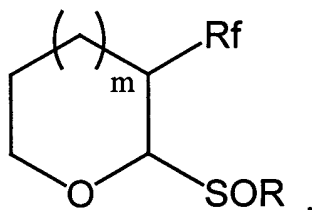


wherein Rf^1 is a fluororous group, Rs^1 is a spacer group, d is 1 or 0, R^4 is an alkyl group or an aryl group, R^5 is an alkyl group or an aryl group, and X is Cl, Br or I.

5 The present invention further provides a compound having the formula:

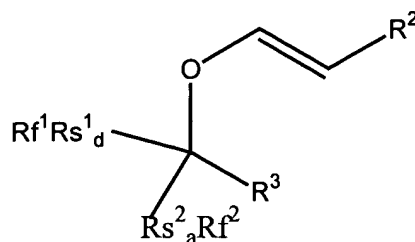


The present invention also provides a compound having the formula:

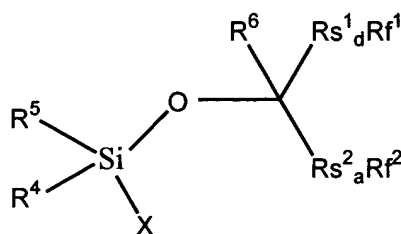


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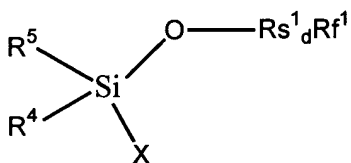
The present invention also provides a compound having the formula:



The present invention also provides a compound having the formula:

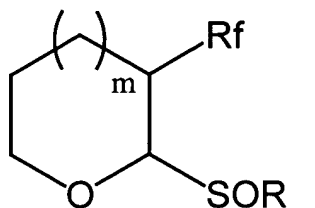


5 . The present invention further provides a compound having the formula:



In another aspect, the present invention provides a method of activating an anomeric sulfoxide to react with an alcohol to form a corresponding ether comprising the step of mixing the anomeric sulfoxide with Cp_2ZrCl_2 , AgClO_4 , and the alcohol. The anomeric sulfoxide can, for example, have the formula:

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In still another aspect, the present invention provides a method of carrying out a reaction comprising the steps of:

- 5 attaching a fluorous tag to a substrate that is bound to a solid support;

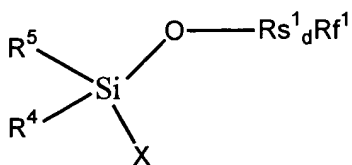
cleaving the fluorous-tagged substrate from the solid support while retaining the fluorous tag attached thereto;

- 10 reacting the cleaved, fluorous-tagged substrate in a liquid phase reaction to synthesize a fluorous-tagged product; and

separating the fluorous-tagged product from other compounds using a fluorous separation technique.

The method may further include the step of cleaving the fluorous tag from the fluorous tagged product.

- 15 In one embodiment, the fluorous tag has the formula:



Brief Description of the Drawings

Figures 1 illustrate synthesis of one embodiment
 5 of a fluorous glycosyl iodide tagging compound of the
 present invention and fluorous-tagged ethers synthesized
 therefrom.

Figures 2 illustrate synthesis of one embodiment
 of a fluorous sulfoxide tagging compound of the present
 10 invention and fluorous-tagged ethers synthesized therefrom.

Figure 3 illustrates synthesis of one embodiment
 of a fluorous vinyl ether tagging compound of the present
 invention and fluorous tagged ethers produced therefrom.

Figure 4 illustrates synthesis of one embodiment
 15 of a fluorous alkoxysilyl tagging compound of the present
 invention and fluorous tagged ethers produced therefrom.

Figure 5 illustrates the tagging of a number of
 alcohols with the fluorous alkoxysilyl tag of Figure 4 and
 subsequent regeneration of the alcohol and recycling of the
 20 fluorous alkoxysilyl tag.

Figure 6 and 7 illustrate synthesis of combinatorial mixtures using the fluororous tag of Figure 3.

Figure 8 illustrates characterization of several products of the synthesis of Figures 6 and 7 (peaks 1-6 correspond to compounds **43-48**, respectively).

Figure 9 illustrates an example of conversion from a solid phase synthesis to a liquid phase synthesis using the fluororous tag of Figure 4.

Detailed Description of the Invention

10 Fluorous-Labeled Tetrahydropyranyl (THP^F) Ethers

In one aspect the present invention provides a series of fluorous-labeled tetrahydropyranyl (THP^F) ethers that are stable to basic and nucleophilic reaction conditions and become readily recyclable after cleavage. A
15 perfluoroalkyl-substituted dihydropyran which can be installed on any hydroxy-bearing substrate via acid catalysis in the same way a standard THP protection is provided as a model.

Initially, dihydropyran **4** was synthesized in one
20 step from perfluorooctyl iodide **3** and dihydropyran **2** in 46% yield as illustrate in Figure 1. However, treatment of alcohols with an excess of **4** using a variety of acids, solvents, and temperatures failed to give any of the desired acetal **5**. The loss of reactivity of the vinyl

ether is believed to be a result of the powerful electron withdrawing effect of the perfluoroalkyl chain.

A second route involved glycosylation methodology. Glycosyl fluorides have been effectively activated by a $\text{Cp}_2\text{ZrCl}_2\text{-AgClO}_4$ reagent system. Suzuki, K. *Pure Appl. Chem.* **1994**, 66, 1557. Fluorous glycosyl iodide **6** was accessible in one step from perfluorooctyl iodide **3** with excess dihydropyran and stoichiometric $\text{Na}_2\text{S}_2\text{O}_4/\text{NaHCO}_3$ under phase transfer conditions in 64% yield.

Unfortunately, this reaction was often irreproducible, and was typically plagued by formation of hemiacetal **7**. Use of catalytic Raney Nickel in refluxing THF gave **6** more reliability in 32-38% yield. Addition of a slight excess of **6** to a solution of one equivalent of Cp_2ZrCl_2 , two equivalents of AgClO_4 , and one equivalent of an alcohol gave good yields of fluorous THP labeled products **8**, presumably via an intermediate highly reactive oxonium species. Deprotection via transacetalization with methanol and catalytic para-toluenesulfonic acid proceeded to give the free alcohol in 80-95% yield, as well as the transacetalization product **9**. However, attempts to recycle methyl THP ether **9** to iodopyran **6** have yet to be successful. Application of trimethylsilyl iodide (TMSI) and several of its *in situ* prepared variants led in all cases to the undesired elimination product **4** as the primary product.

A sulfoxide method, however, has proven to be a mild and effective means for constructing glycosidic linkages. See Yan, L.; Kahne, D. J. *Am. Chem. Soc.* **1996**,

118, 9239, and references cited therein. The synthesis of fluorous tetrahydropyranyl (THP^F) ethers of the present invention using this technique, began with the direct synthesis of methyl THP ether **9** from perfluorooctyl iodide **3** and dihydropyran **2**. Treatment of a methanolic solution of **3** and 5 mol% [CpFe(CO)₂]₂ (cyclopentadienyl iron dicarbonyl dimer) with 1.5 equiv of dihydropyran and 1.1 equiv of Et₃N at room temperature gave **9** in 83% yield. Conversion of **9** to the phenylthioacetal **10** was first accomplished using Nicolaou's method (5 equiv PhSSiMe₃ (phenylthiotrimethylsilane), 1.2 equiv Me₃SiOTf (trimethylsilyltrifluoromethanesulfonate)) to give **10** in 60% yield. Nicolaou, K. C.; Seitz, S. P.; Papahatjis, D. P. *J. Am. Chem. Soc.* **1983**, *105*, 2430. Alternatively, heating **9** in a 1:1 mixture of PhSH (thiophenol) and toluene at 100 °C with 1 equiv of para-toluenesulfonic acid gave **10** in 61% yield. Oxidation of sulfide **10** with a Na₂HPO₄-buffered solution of meta-chloroperoxybenzoic acid in dichloromethane at 0 °C provided fluorous sulfoxide tagging compound **11** as a 1.5:1 mixture of anomers in 72% yield. Subsequent conversion utilized the major, more reactive *cis*-isomer. *Trans*-**11** could be recycled to a 1:1 mixture of anomers in thiophenol/dioxane (1:1) at 95 °C in the presence of a catalytic amount of HgSO₄.

Attempted glycosylation of alcohols with **11** using the standard triflic anhydride/2,6-di-*tert*-butyl-4-methylpyridine reagent system gave low yields of **8** contaminated with large amounts of a dihydropyran elimination product **4**. In contrast, treatment of a 1:2:1 mixture of Cp₂ZrCl₂, AgClO₄, and alcohol at -20 °C with 1.5-2.5 equivalents of **11**

provided after 8-10 h the desired fluorous THP labeled ethers **12-20** illustrated in Figure 2 (ROTHP^F) in good yields for 1° and 2° alcohols. In addition, deprotection of the THP^F-ethers and recycling of the protective group was
5 accomplished by a transacetalization reaction using 25 mol% para-toluenesulfonic acid in MeOH:THF (2:1) at 70 °C for 20-30 h to give good yields of recovered alcohols and **9**.

Purification of most THP^F-ethers was accomplished simply by dissolving the crude product in MeCN and
10 extracting five times with FC-72. FC-72 is a fluorocarbon solvent commercially available (3M) which includes perfluorohexane (C₆F₁₄) isomers (bp 56 °C). Concentration of the fluorous extracts yielded the fluorous product, which contained small amounts of a dihydropyran elimination
15 product **4**, as well as trace amounts of unreacted sulfoxide **11**. After this extraction, only minor amounts of the fluorous product remained in the MeCN layer. The crude deprotection mixture, treated with the same MeCN/FC-72 extraction procedure, gave the fluorous methyl-THP ether **8**
20 in the FC-72 extracts, while the deprotected alcohol was found in the organic layer. As the organic mass or the polarity of a fluorous THP-labeled substrate becomes larger, however, simple liquid-liquid extraction becomes inefficient. Solid phase extraction by filtration through
25 fluorous reverse-phase (FRP) silica gel was found to be effective for these cases. See Curran, D. P.; Hadida, S.; He, M. J. *Org. Chem.* **1997**, 62, 6714. The rather polar **5** is almost insoluble in FC-72. This is advantageous in terms of separation of excess **11** during extractive purification
30 of THP^F-labeled alcohols, but also suggests a sufficiently

polar moiety on the substrate to be protected may overpower the fluorous nature of the protected product. Fluorous THP-labeled cholesterol and methyl mandelate could not be fully extracted from MeCN with multiple (15) FC-72 extractions. Loading of the crude product onto a MeCN-wetted FRP-SiO₂ column, washing first with MeCN to elute organic components, then with FC-72 to elute the fluorous labeled compounds, conveniently allowed separation of THP^F-labeled ethers from organic side products.

10 The recyclable fluorous THP tag or protecting group enables simple purification of small molecules by liquid-liquid extraction with FC-72/MeCN, and of larger or more polar molecules by solid phase extraction with fluorous reverse phase silica gel.

15 **Fluorous Vinyl Ether Tags**

In another aspect, the present invention provides a recyclable fluorous vinyl ether tagging or protecting group that is attached and removed under mildly acidic conditions.

20 A representative example of the synthesis of a fluorous vinyl ether tagging compound is illustrated in Figure 3. The synthesis of vinyl ether **23** begins with commercially available iodide **21**. Formation of the Grignard reagent from **21** was effectively accomplished with
25 sonication for the reaction initiation. Thus, treatment of an ether suspension of excess magnesium powder with 0.1 equivalents of **21**, sonication for 20 minutes, and

subsequent addition of an additional 2.4 equivalents of **21** in Et₂O provided the Grignard reagent after a two hour reflux period. Dropwise addition of one equivalent of ethyl formate to the reaction mixture and further refluxing for 5 h gave the crude fluorous alcohol **22** after standard workup. This compound was conveniently purified by washing the crude solid with dichloromethane to give a 93% yield of **22**. Vinylation (See Faulkner, D. J.; Petersen, M. R. *J. Am. Chem. Soc.* **1973**, 95, 553) of **22** with 0.5 equivalents of mercuric acetate in a 1:1 mixture of ethyl vinyl ether and FC-72 at 45 °C for 40 h gave fluorous vinyl ether tagging compound **23** in 51% yield, with 42% recovered alcohol **22** (88% yield based on recovered starting material). The extremely apolar **23** could be isolated by filtration of the crude product mixture through a short pad of SiO₂ with hexanes, since the R_F value of **23** is 0.9 in hexane, while **22** has an R_F close to zero in hexane. The R_F value of a compound is a measure of the relative polarity of the compound in a given solvent system. Thus, a compound with R_F=1 is very nonpolar relative to a compound with R_F=0, which would be considered very polar. The unreacted **22** can then be resubjected to the vinylation reaction, allowing for a ~70% conversion to **23** after two runs. Accordingly, vinyl ether **23** is readily prepared in multigram quantities.

Protection of alcohols with **23** proceeds under mildly acidic conditions. Treatment of an Et₂O solution of 1 equivalent of a primary alcohol and 3 equivalents of **23** with 5 mol% of camphorsulfonic acid for 3 h at room temperature provided the desired protected alcohols **24** (ROAE^F) in 84-93% yields, with the majority of the excess of

vinyl ether recoverable. Secondary and even tertiary alcohols are similarly protected in good yields using THF as solvent at 65° C for 30-45 min. The moderate yield obtained for protection of *tert*-butyl alcohol compares
5 nonetheless well to the protection of this sterically hindered and volatile substrate with the fluorous THP^F lable discussed above. The alkoxy ethyl (**AE^F**) fluorous label could also be installed on the nitrogen atom of an aniline. All protected and fluorous-tagged substrates were purified
10 from excess **23** by column chromatography on SiO₂. Separation was generally very straightforward as a result of the considerable R_F-differences between **23** and **24**, and the pre-purification of the reaction mixture from organic impurities by extraction with FC-72.

15 Deprotection of fluorous acetals **25-31** proceeded under mild conditions as well. Treatment of the protected substrates in a 1:1 solution of Et₂O and MeOH with 5 mol% of camphorsulfonic acid gave, after 1 h, excellent yields of deprotected substrates as well as a quantitative
20 recovery of fluorous alcohol **22** (see Figure 3). After completion of the reaction, the products were isolated in pure form by simple 3-phase extraction (reaction mixture / saturated aqueous NaHCO₃ / FC-72). Alcohol **22** can be resubjected to vinylation to give **23** and thus is
25 efficiently recycled.

The recyclable, highly fluorous acetal protecting group have broad applications in fluorous synthesis as well as in fluorous/solid phase combinations and other parallel

synthesis strategies. The precursor vinyl ether **23** can be prepared in large quantities in a straightforward two step reaction sequence. Primary, secondary, and tertiary alcohols can be protected in good to excellent yields. The
5 N-protection of 2-fluoroaniline also demonstrates the feasibility of using **23** with amines. After protection with the AE^{F} -groups of the present invention, a compound is capable of undergoing a series of reactions in which purification of products can, for example, be accomplished
10 by simple liquid-liquid extraction with FC-72 or filtration through fluorous reverse-phase SiO_2 . Deprotection occurs under mild acidic conditions, and the fluorous label is easily isolated and effectively recycled.

Compared to the THP^{F} -function described above, the
15 AE^{F} -groups of the present invention are more readily cleaved and recycled and have a higher affinity toward the fluorous environment. There is a direct correlation between the number of fluorine atoms in a molecule and its selective solubility in perfluorinated solvents. With the exception
20 of small organic molecules, most compounds protected with the THP^{F} -function were insufficiently fluorous for efficient liquid-liquid extraction and rapid purification required fluorous reverse-phase SiO_2 (FRP). In particular in preparative scale synthesis, the broad use of FRP
25 chromatography is currently limited by the high costs of the stationary phase. Because of the higher level of fluorination of the AE^{F} -group, all substrates shown in Figure 3 could be purified by simple liquid-liquid extraction. The AE^{F} -group tags or labels are, therefore,
30 ideally suited for the protection of large quantities or

high molecular weight organic molecules under basic and/or nucleophilic reaction sequences. Application of the AE^F-fluorous tagging compounds of the present invention to a combinatorial synthesis of analogs of the antimitotic natural product curacin A is discussed below.

tert-Butyl-phenyl-1H,1H,2H,2H-heptadecafluorodecyloxysilyl (BPFOS) Tags

In still another aspect, the present invention provides fluorous alkoxysilyl tagging groups. In general, *tert*-Butyl-phenyl-1H,1H,2H,2H-heptadecafluorodecyloxysilyl (BPFOS) ethers resulting from reaction of the fluorous alkoxysilyl tagging groups of the present invention with alcohols were found to be surprisingly acid stable and allow simple protection-purification-deprotection schemes by liquid-liquid extraction with FC-72/CH₃CN or by solid phase extraction with fluorous reverse phase silica gel.

Given the acid stability of bis-alkoxysilyl ethers, the viability of fluorous alkoxysilyl groups as fluorous tagging/protecting groups for alcohols was explored. A secondary alcohol, cyclohexanol, was chosen as a model compound for tagging. As illustrated in Figure 4, fluorous alkoxysilyl ethers (**34a,b**) were readily prepared by reacting stoichiometric amounts of commercially available dichlorosilanes **32** with fluorous alcohol **22** to yield chlorosilanes **33a,b**, which were however contaminated with the bis-adduct of the fluorous alcohol. Without purification, **33a,b** were used to protect cyclohexanol as illustrated in Figure 4. The ensuing mixture was purified by solid phase extraction on fluorous reverse phase silica

gel with hexane/acetone (50:1). The indicated yields were isolated yields after separation from bis-adducts of the fluoros alcohol. Conversion based on cyclohexanol was quantitative.

Alkoxysilyl ether **37a** was derived from bromosilane **36**, which can easily be obtained in high yield and purity in a two step sequence starting from *tert*-butyldiphenylsilylchloride (TBDPS-Cl) and alcohol **35** as illustrated in Figure 4.

Fluorous alkoxysilyl ethers (**34a,b**, **37a**) were each dissolved in a mixture of CH₂Cl₂/trifluoroacetic acid (5%), and aliquots of these solutions were quenched with MeOH/pyridine (20:1). The quenched reaction mixtures were analyzed for remaining **34a,b** and **37a** by LC-MS (Liquid chromatography-mass spectrometry). Reactions and quenching were performed on a HP 7868 solution phase synthesizer. Analysis of quenched samples was done with a HP 1100 series LC/MS. Samples eluted were compared with unreacted control samples. (R_t [min]: 2.6 (**34a**), 2.9 (**34b**), 2.3 (**37a**); Novapak C18, 3.9 x 150 mm, 1.2 mL/ min, MeOH as eluent).

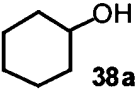
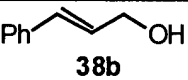
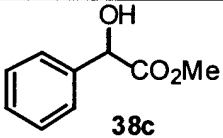
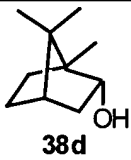
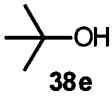
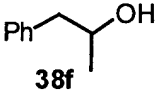
The stability of these alkoxysilyl ethers appeared to be determined by the steric bulk around the silicon atom. While **34a** was not very stable ($t_{1/2}$ ~ 6 min) under the acidic reaction conditions, **34b** ($t_{1/2}$ ~ 4 h) was moderately stable, and the *tert*-butyl-phenyl-1H,1H,2H,2H-heptadecafluorodecyloxysilyl ether **37a** ($t_{1/2}$ >> 6 h) was very stable. These results prompted investigation of the chemical behavior of **37a** in somewhat greater detail. As a

result of the enhanced electrophilicity of the silicon atom in bis-alkoxysilyl ethers, the latter are generally more labile toward nucleophiles and bases than either the TBDPS or the *tert*-butyldimethylsilyl (TBDMS) groups. Yet, after
5. dissolving **37a** in a mixture of THF- d_8 and 0.25 M NaOD (3:1), a $t_{1/2}$ of 48 h was determined by 1H NMR, suggesting that the *tert*-butyl-phenyl-1H,1H,2H,2H-hepta-decafluorodecyloxysilyl (BPFOS) tag can be used in mildly basic aqueous media. In contrast, the stability under protic acidic conditions in
10 5% p-TsOH/MeOH ($t_{1/2}$ ~ 40 min) is more limited. Based on these results, it appears that the BPFOS group is closely related in stability to the *tert*-butylmethoxyphenylsilyl group, which is slightly more acid-labile than the TBDPS function but considerably more acid-stable than a TBDMS-
15 ether.

The viability of the *tert*-butyl-phenyl-1H,1H,2H,2H-hepta-decafluorodecyloxysilyl (BPFOS) protecting group for the protection of alcohols in a parallel synthesis experiment performed on a HP 7868 solution phase
20 synthesizer was also studied. Silylbromide **36** was reacted with a panel of alcohols to yield the bis-alkoxysilyl ethers **37a-f** as illustrated in Figure 5. In general, alcohols **38a-f** (0.16 mmol) were added to a solution containing the appropriate amount of reagents in 0.7 mL of
25 CH_2Cl_2 . The samples were vortexed and left for 16 h. The solutions were washed with H_2O , the organic phase was evaporated and the residue was eluted with hexane through cartridges containing SiO_2 .

Table 1 summarizes data for the protection of alcohols **38a-f** with **36** as set forth in the following equation (and deprotection of silyl ethers with TBAF (tetrabutylammonium fluoride)). [1] Yields were based on isolated and characterized material (^1H NMR, MS) and were slightly lower than reported for the bulk synthesis of **37a** as a result of loss of material in the liquid-liquid extraction steps on the synthesizer. Purification in the deprotection step was via FC-72/ CH_3CN liquid-liquid extraction and filtration through silica gel, and provided material of >90% purity. During the deprotection step, silyl ethers **37a-f** were added to a solution of TBAF (0.6 M) in 0.5 mL of THF. After 3 hours, Et_2O was added, the solutions were washed with H_2O (3 times), the Et_2O phase was collected, evaporated and the residue was partitioned between FC-72 and CH_3CN . The organic phase was eluted with hexane/ AcOEt through a SiO_2 cartridge.

Table 1

| Entry | R-OH | Yield for BPFOS attachment [%] | Yield for BPFOS cleavage [%] |
|-------|---|--------------------------------|------------------------------|
| 1 |  38a | 79 | 77 |
| 2 |  38b | 77 | 88 |
| 3 |  38c | 24 | nd |
| 4 |  38d | 83 | 94 |
| 5 |  38e | 27 | nd |
| 6 |  38f | 62 | 100 |

Primary and secondary alcohols gave excellent to fair yields in the protection and deprotection steps while, probably for steric reasons, the tertiary alcohol *t*-butanol (entry 5) and the sterically demanding methyl mandelate (entry 3) provide less favorable yields.

In summary, new acid stable fluorous silane tag suitable for the protection of primary and secondary alcohols have been developed. The tag is easily attached

and removed in an automated parallel synthesis setup and allows for purification of intermediates and products via fluorous liquid-liquid or solid phase extraction.

Exemplary Applications

Two model applications serve to illustrate the potential use of the newly developed fluorous tags of the present invention. For example, Figure 6 illustrates the preparation of aldehyde **39** which is subjected to an *in situ* obtained mixture of six organolithium reagents. The excess of reagents converts the aldehyde rapidly to adduct **40**, which is trapped by addition of AE^Fvinyl ether tag **23** as illustrated in Figure 7. Only the desired secondary alcohol products are rendered fluorous with this approach and converted to acetals **41**, which are readily purified by fluorous techniques, or, if required, by chromatography. The stability of the AE^F protective group allowed easy manipulation of these products even in an aqueous basic environment, conditions that would lead to immediate decomposition of the earlier silyl ether based tags. After separation from the byproducts and reagents, compounds **41** are de-tagged, and the desired mixture of alcohols **42** is obtained in high yield ready for biological testing. The very high level of combinatorial mixture purification that can be obtained with this approach is demonstrated by the LC-MS trace shown in Figure 8.

Figure 9 illustrates a powerful application for the use of BPFOS tagging compound **36**, and demonstrates the first example of a solid phase - fluorous phase switch.

Addition of Grignard reagent to the bead-linked aldehyde derived from **49** provides alcohol **50** which is tagged/protected as BPFOS-ether **51** and thus rendered both solid and fluorous. After acidic (TFA) cleavage of the solid support, the BPFOS tagging group allows the extraction of product **52** into the fluorous environment, and subsequent solution phase chemistry can immediately take advantage of fluorous phase purification techniques. No existing fluorous silyl ether tag has the stability necessary to allow this conversion.

Experimental Examples

Compounds **12-20**, were obtained in pure form and fully characterized. **Cis-11**: Mp 66-69 °C; IR (KBr) 3063, 2919, 2853, 1664, 1603, 1445, 1199 cm⁻¹; ¹H NMR (CDCl₃) δ 8.00-7.90 (m, 2 H), 7.70-7.55 (m, 3 H), 4.87 (d, 1 H, *J* = 4.3 Hz), 4.50 (dt, 1 H, *J* = 11.5, 3.4 Hz), 3.72-3.66 (m, 1 H), 3.17-3.00 (m, 1 H), 2.64-2.56 (m, 1 H), 2.05-1.75 (m, 4 H); ¹³C NMR (CDCl₃) δ 136.5, 134.3, 129.3, 128.9, 125.0-105.0 (m, 8 C), 85.6, 63.3, 32.4 (t, 1 C, *J* = 20.1 Hz), 19.9, 17.5; MS (CI) *m/z* (rel. intensity) 629 ([M+H]⁺).

General Procedure for Glycosylation. A mixture of 200 mg of powdered molecular sieves (4Å), zirconocene dichloride (139 mg, 0.48 mmol), silver perchlorate (200 mg, 0.96 mmol), and 5 mL of CH₂Cl₂ was stirred at room temperature for 10 min. Benzyl alcohol (49.0 μL, 0.47 mmol) was added to the yellow solution, and the temperature was lowered to -20 °C. A solution of **cis-11** (446 mg, 0.71 mmol) in 10 mL

of CH₂Cl₂ was added, and the reaction mixture was allowed to warm gradually to room temperature. After 10 h, the solution was filtered through a pad of SiO₂. After rinsing with CH₂Cl₂, the filtrate was concentrated and the residue partitioned between 4 mL of MeCN and 15 mL of FC-72. The MeCN layer was washed with 4 additional 10-15 mL portions of FC-72. ¹H NMR of the combined fluorous extracts showed the desired product **14** as well as elimination product **4** in a 5.3:1 ratio. ¹H NMR of the MeCN layer showed primarily excess sulfoxide **11**. Chromatography of the FC-72 extract on SiO₂ (hexanes/Et₂O, 97:3) provided pure **14** (264 mg, 0.43 mmol, 92%) as a colorless solid (7.4:1 ratio of diastereomers): Mp 36-37 °C; IR (KBr) 3037, 2966, 2879, 1501, 1450, 1358, 1209, 1147 cm⁻¹; Major diastereomer: ¹H NMR δ (CDCl₃) 7.37-7.29 (m, 5 H), 4.99 (d, 1 H, *J* = 3.5 Hz), 4.80 (d, 1 H, *J* = 11.6 Hz), 4.54 (d, 1 H, *J* = 11.7 Hz), 3.97-3.90 (m, 1 H), 3.63 (dt, 1 H, *J* = 11.3, 5.0 Hz), 2.60-2.40 (m, 1 H), 2.20-2.09 (m, 1 H), 1.90-1.80 (m, 2 H), 1.60-1.50 (m, 1 H); ¹³C NMR δ (CDCl₃) 137.4, 128.5, 128.0, 125.0-105.0 (m, 8 C), 95.2, 69.6, 61.0, 41.3 (t, 1 C, *J* = 19.5 Hz), 21.9, 18.7, 17.4; HRMS (EI) calculated for C₂₀H₁₅O₂F₁₇ 610.0801, found 610.0803.

General Procedure for Deprotection of ROTHF^F-tagged compounds. A solution of **14** (112 mg, 0.18 mmol) and p-toluenesulfonic acid (9 mg, 0.05 mmol) in 2 mL of MeOH and 2 mL of THF was heated at 70 °C for 24 h. The reaction mixture was diluted with Et₂O and washed with a saturated NaHCO₃ solution. The organic layer was dried (Na₂SO₄), concentrated, and partitioned between 2 mL of MeCN and 8 mL of FC-72. The MeCN layer was washed with three 8 mL

portions of FC-72. ^1H NMR analysis of the combined FC-72 extracts showed **9** (82 mg, 0.15 mmol, 84%) with a trace amount of **4**. ^1H NMR analysis of the MeCN layer showed pure benzyl alcohol (19.0 mg, 0.176 mmol, 96%).

5 **Preparation of 22:** A suspension of 4.2 g (0.173 mmol) of Mg powder and 2.5 g (4.36 mmol) of iodide **21** in 20 mL of Et₂O was sonicated for 20 min. To this black mixture was added dropwise a solution of 22.5 g (39.2 mmol) of iodide **21** in 150 mL of Et₂O. The reaction mixture was heated at
10 reflux for 2 h, and the solution was cannulated away from the excess Mg into a new flask. After dropwise addition of 1.40 mL (17.4 mmol) of ethyl formate, the black solution was heated at reflux for 5 h. The reaction mixture was cooled to 0 °C, quenched with saturated ammonium chloride
15 solution and extracted with Et₂O. The organic extracts were dried (Na₂SO₄) and concentrated. The crude product was washed with CH₂Cl₂ and dried in vacuo to give 14.92 g (16.15 mmol, 93%) of **22** as a white solid: Mp 98-101 °C; IR (KBr) 3461, 1204, 1146 cm⁻¹; ^1H NMR (CDCl₃) δ 4.20 (d, 1 H, J = 6.0 Hz), 3.80-3.73 (m, 1 H), 2.60-2.15 (m, 4 H), 1.95-
20 1.65 (m, 4 H); ^{13}C NMR (TFA) δ 125.0-105.0 (m, 16 C), 79.4, 28.4, 25.9; MS (EI) m/z (rel. intensity) 907 ([M-OH]⁺, 2), 887 (6), 477 (100).

Preparation of 23: A mixture of 14.92 g (16.15 mmol) of
25 **22**, 2.6 g (8.1 mmol) of Hg(OAc)₂, 100 mL of ethyl vinyl ether, and 100 mL of FC-72 (commercially available from 3M) was heated at reflux for 40 h. After cooling to room temperature, the reaction mixture was transferred to a

separatory funnel, and the layers were separated. The organic layer was extracted with FC-72 (3x), and the combined FC-72 extracts were dried (Na₂SO₄), and concentrated. The crude product was loaded onto a short
 5 (1.5") pad of SiO₂ and washed with hexanes until no more **23** was shown to be eluting via TLC. The hexane washings were concentrated to give 7.85 g (8.2 mmol, 51%) of **23** as a white solid, Mp 36-38 °C. Flushing the SiO₂ pad with EtOAc, followed by concentration of the filtrate gave 6.29
 10 g (6.8 mmol, 42%) of **22**. Spectroscopic data for **23**: IR (KBr) 3131, 1646, 1617, 1209, 1151 cm⁻¹; ¹H NMR (CDCl₃) δ 6.27 (q, 1 H, *J* = 6.6 Hz), 4.35 (d, 1 H, *J* = 14.2 Hz), 4.10 (d, 1 H, *J* = 6.5 Hz), 3.91 (p, 1 H, *J* = 5.5 Hz), 2.35-2.00 (m, 4 H), 1.95-1.75 (m, 4 H); ¹³C NMR (CDCl₃) δ 150.0,
 15 125.0-105.0 (m, 16 C), 89.8, 76.4, 26.7 (t, *J* = 22.1 Hz), 24.8; MS (EI) *m/z* (rel. intensity) 950 (*M*⁺, 7), 887 (20), 391 (100).

Protection of cinnamyl alcohol: To a solution of 10.5 mg (0.08 mmol) of cinnamyl alcohol and 223 mg (0.24 mmol) of
 20 **23** in 3 mL of Et₂O was added 1 mg (5 mol%) of 10-campfersulfonic acid (CSA). The solution was stirred at room temperature for 3 h. Saturated NaHCO₃ solution was added, and the reaction mixture was extracted with FC-72 (3x). The combined FC-72 extracts were dried (Na₂SO₄), and
 25 concentrated. Column chromatography on SiO₂ (hexanes/Et₂O, 95:5) gave 101 mg (0.11 mmol, 64%) of **23** and 79 mg (0.073 mmol, 93%) of the desired AE^F-protected cinnamyl alcohol as a colorless oil: IR (neat) 3032, 2981, 1491, 1204, 1148, 907 cm⁻¹; ¹H NMR (CDCl₃) δ 7.38-7.21 (m, 5 H), 6.60 (d, 1 H,

$J = 15.9$ Hz), 6.25 (dt, 1 H, $J = 5.9, 15.9$ Hz), 4.81 (q, 1 H, $J = 5.3$ Hz), 4.26-4.13 (m, 2 H), 3.80 (p, 1 H, $J = 5.5$ Hz), 2.40-2.00 (m, 4 H), 1.90-1.75 (m, 4 H), 1.37 (d, 3 H, $J = 5.2$ Hz); ^{13}C NMR (CDCl_3) δ 136.6, 132.4, 128.7, 127.9, 126.5, 125.4, 125.0-105.0 (m, 16 C), 99.0, 73.4, 65.8, 26.4, 20.4; MS (EI) m/z (rel. intensity) 951 ($[\text{M}-\text{OCH}_2\text{CHCHPh}]^+$, 9), 887 (9), 577 (8), 477 (50), 118 (100).

Deprotection of AE^{F} -protected cinnamyl alcohol: A solution of 71 mg (0.065 mmol) of $\text{AE}^{\text{F}}-\text{OCH}_2\text{CH}=\text{CH}-\text{Ph}$ and 1 mg (5 mol%) of CSA in 1 mL of MeOH and 1 mL of Et_2O was stirred at room temperature for 1 h. The reaction mixture was then transferred to a separatory funnel, and saturated NaHCO_3 solution and FC-72 were added. The organic and aqueous layers were washed with FC-72 (3x). The combined FC-72 extracts were dried (Na_2SO_4), and concentrated to give 60 mg (100%) of **22**. The organic layer was dried (Na_2SO_4), and concentrated to give 8.6 mg (98%) of cinnamyl alcohol.

Preparation of 34b: A solution of dichlorodiphenylsilane (0.7 mmol), alcohol **22** (0.7 mmol) and triethylamine (0.77 mmol) in a mixture of CH_2Cl_2 (2.5 mL) and benzotrifluoride (BTF, 2.5 mL) was heated at reflux for 1.5 d. Solvents were evaporated and the residue was partitioned between FC-72 and CH_2Cl_2 . The FC-72 phases were combined and evaporated. The residue was dissolved in CH_2Cl_2 (5 mL). Cyclohexanol (0.47 mmol), triethylamine (0.65 mmol) and dimethylamino-pyridine (DMAP, 0.02 mmol) were added and the mixture was stirred at room temperature overnight. 3-Phase extraction (NaHCO_3 solution, CH_2Cl_2 , FC-72) yielded after pooling and

evaporation of the FC-72 phase a colorless oil. Filtration over fluorous reverse phase silica (hexane/acetone 50:1) gave 0.24 g (47%) of **34b** as a colorless oil which solidified upon standing: ^1H NMR (CDCl_3) δ 7.62–7.59 (m, 4 H), 7.45–7.35 (m, 6H), 3.98–3.92 (m, 1H), 3.82–3.73 (m, 1H), 2.3–1.9 (m, 4H), 1.9–1.6 (m, 8H), 1.5–1.3 (m, 3H), 1.2–1.0 (m, 1H); ^{13}C NMR (CDCl_3) δ 134.9, 132.8, 130.5, 128.0, 125–105 (m, 16C), 71.8, 70.6, 35.5, 27.4, 27.2 (b), 25.4, 23.9; MS(EI) m/z (rel. intensity) 1204 (M^+ , 4), 1185 (5), 1126 (85).

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Preparation of 37a: A solution of TBDPS-Cl (26.5 mmol), alcohol **35** (24.1 mmol), DMAP (1.2 mmol) and imidazole (33.8 mmol) in CH_2Cl_2 (50 mL) was stirred at room temperature overnight. CH_2Cl_2 was added and the solution was washed with H_2O , 1 M HCl and brine. Drying (Na_2SO_4) and evaporation of the solvent yielded the TBDPS ether as a colorless oil: 15.5 g (92%) ^1H NMR (CDCl_3) δ 7.69–7.66 (m, 4 H), 7.45–7.38 (m, 6H), 3.96 (t, 2H), 2.45–2.25 (m, 2H), 1.07 (s, 9H); ^{13}C NMR (CDCl_3) δ 135.2, 134.9, 129.9, 127.9, 125–105 (m, 8C), 56.3, 33.9 (b), 26.6, 19.1.

Bromine (26.5 mmol) was added dropwise to a solution of the TBDPS ether (22.1 mmol) in 1,2-dichloroethane (150 mL) at 0°C . Stirring continued at room temperature overnight. Distillation (0.03 mbar/ 105–110°C) yielded 11.3 g (72%) of **36** as a colorless oil: ^1H NMR (CDCl_3) δ 7.69–7.65 (m, 2 H), 7.48–7.39 (m, 3H), 4.11–4.06 (m, 2H), 2.47–2.35 (m, 2H), 1.01 (s, 9H); ^{13}C NMR (CDCl_3) δ

. 135.6, 134.9, 131.1, 128.1, 125-105 (m, 8C), 57.0, 34.0
(b), 25.1, 21.4.

36 (1.1 mmol) was dissolved in CH₂Cl₂ (5 mL).
Cyclohexanol (1 mmol), triethylamine (1.4 mmol) and
5 dimethylaminopyridine (DMAP, 0.05 mmol) were added and the
mixture was stirred at room temperature overnight. CH₂Cl₂
was added and the mixture was washed with NaHCO₃ solution.
The organic phase was dried (Na₂SO₄), the solvent was
removed and the residue filtered through SiO₂ (hexane/EtOAc
10 98:2) to give 0.70 g (97%) of **37a** as a colorless oil: ¹H NMR
(CDCl₃) δ 7.65-7.60 (m, 2H), 7.42-7.35 (m, 3H), 4.11 (t, 2H,
J = 6.9 Hz), 3.95-3.88 (m, 1H), 2.50-2.35 (m, 2H), 1.84-
1.72 (m, 4H), 1.52-1.40 (m, 3H), 1.30-1.21 (m, 3H), 0.94
(s, 9H); ¹³C NMR (CDCl₃) δ 135.5, 132.3, 129.9, 127.8, 125-
15 105 (m, 8C), 71.1, 55.7, 35.7, 34.1 (b), 26.1, 25.6, 23.7,
18.8; HR-MS(EI) *m/z* found 723.1597, calcd 723.1587.

Reactions and quenching were performed on a HP
7868 solution phase synthesizer. Analysis of quenched
samples was done with a HP 1100 series LC/MS. Samples
20 eluted were compared with unreacted control samples. (*R*_t
[min]: 2.6 (**34a**), 2.9 (**34b**), 2.3 (**37a**); Novapak C18, 3.9 x
150 mm, 1.2 mL/ min, MeOH as eluent).

Protection of alcohols 38a-f. Alcohols **38a-f** (0.16 mmol)
were added to a solution containing the appropriate amount
25 of reagents in 0.7 mL of CH₂Cl₂. The samples were vortexed
and left for 16 h. The solutions were washed with H₂O, the
organic phase was evaporated and the residue was eluted
with hexane through cartridges containing SiO₂.

Deprotection of ethers 37a-f. Silyl ethers 37a-f were added to a solution of TBAF (0.6 M) in 0.5 mL of THF. After 3 h, Et₂O was added, the solutions were washed with H₂O (3 times), the Et₂O phase was collected, evaporated and the residue was partitioned between FC-72 and CH₃CN. The organic phase was eluted with hexane/AcOEt through a SiO₂ cartridge.

Although the present invention has been described in detail in connection with the above examples, it is to be understood that such detail is solely for that purpose and that variations can be made by those skilled in the art without departing from the spirit of the invention except as it may be limited by the following claims.